Soliton-like Spin State in the A-like Phase of ^{3}He in Anisotropic Aerogel

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Abstract

We have found a new stable spin state in the A-like phase of superfluid ^{3}He confined to intrinsically anisotropic aerogel. The state can be formed by radiofrequency excitation applied while cooling through the superfluid transition temperature and its NMR properties are different from the standard A-like phase obtained in the limit of very small excitation. It is possible that this new state is formed by textural domain walls pinned by aerogel.

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1 Introduction

Recently it was found[1] that the anisotropy of aerogel samples significantly affects the superfluid properties of ^{3}He in aerogel. In particular, NMR properties of the A-like superfluid phase in anisotropic aerogel samples qualitatively correspond to the properties of the superfluid A-phase of bulk ^{3}He with the order parameter vector $\mathbf{l}$ fixed with respect to the sample[1, 2]. One of the crucial properties that point to the anisotropy of the sample is the negative NMR shift in the A-like phase in certain orientations of external static magnetic field $\mathbf{H}$. The analysis of data obtained in superfluid ^{3}He in aerogel over

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the last decade shows that at least some of the aerogel samples are intrinsically anisotropic, meaning that either the procedure of their growth leads to different "porosity" in one of the directions (namely the axis of cylindrical samples) or the samples get irreversibly deformed at one of the stages of making the experimental cell. The theoretical findings are that large enough anisotropy destroys the state that would have existed in isotropic aerogel[3, 4] and stabilizes a phase with the bulk A phase order parameter corresponding to a spatially uniform Anderson-Brinkman-Morel (ABM) order parameter.

Here we present results which show that in the A-like phase in anisotropic aerogel apart from the spin state with properties corresponding to the ABM order parameter a state with quite different NMR properties can exist.

2 Experimental details

We have performed NMR experiments in two samples of 98.2% open silica aerogel in the superfluid A-like phase of ^{3}He. Both samples had a cylindrical shape. The first one was 4 mm in diameter and 3.5 mm in height (sample 1), the other was 5 mm in diameter and 1.5 mm in height (sample 2). The experimental cells were made from Stycast-1266 epoxy and the walls of the cells did not compress the samples at low temperatures when the epoxy shrunk. In that sense the anisotropy (if any) of these aerogel samples was intrinsic. Experiments were performed at pressures of 26.0 bar (sample 1) and 28.6 bar (sample 2) in magnetic fields from 40 to 467 Oe (corresponding to NMR frequencies from 132 to 1517 kHz).

Apart from the longitudinal field solenoid (which produced a static magnetic field oriented parallel to the axes of the cylindrical samples $\hat{\mathbf{z}}$) we had a coil that produced a static field in the direction perpendicular to the longitudinal field and to the direction of the RF (radio-frequency) excitation field. It allowed us to rotate $\mathbf{H}$ by any angle. The homogeneity of the transverse external field was much worse than that of the longitudinal field (10^{-3} and 2×10^{-4} respectivly).

For longitudinal NMR experiments in sample 1 we had a high-Q circuit which consisted of cold capacitors with teflon dielectric (C=0.5 μF) and a superconducting NbTi coil (300 turns) with its axis parallel to $\hat{\mathbf{z}}$. The resonant frequency of the circuit was 9095 Hz, and the quality factor was 1860. In the experiments with this sample we also used another NbTi coil for transverse NMR (80 turns). We did not have the longitudinal NMR

circuit in the experiments with sample 2 and had a copper coil (∼60 turns) for the transverse NMR.

We used a quartz tuning fork resonator for the thermometry[5]. It was calibrated against a vibrating wire resonator and proved very reliable.

3 Results

The properties of the A-like phase were very similar in both aerogel samples and no qualitative difference in the NMR properties was found at different NMR frequencies for a given orientation of **H**. Continuous wave (CW) NMR measurements have shown that the superfluid in our samples manifests properties similar to those observed in an anisotropic aerogel sample squeezed along its axis[1]. In particular, in the A-like phase the NMR shift in longitudinal field ($\mathbf{H}\| \hat{\mathbf{z}}$) was negative and in transverse field ($\mathbf{H}\perp \hat{\mathbf{z}}$) it was positive. Thus we suggest that in our samples the A-like phase corresponds to the A phase of bulk ^{3}He with the order parameter vector **l** fixed with respect to the aerogel sample[2]. However, in both samples we were able to create a novel spin state which is not known for the bulk A phase: while cooling down in transverse field through the superfluid transition temperature T_{ca} in the range $\sim(1.02\div 0.97)T_{ca}$ we repeatedly applied tipping pulses of a certain amplitude every few seconds for five to ten minutes. Fig. 1 shows CW NMR lines obtained after performing such a procedure for several tipping pulse amplitudes compared to the NMR line obtained on cooling down without any pulses. It is clear that the A-like phase enters different spin states depending on whether or not the tipping pulses of sufficiently large amplitude were applied in the mentioned temperature range. We call the former the *disturbed* state and the latter the *undisturbed* state. For the tipping angle of 12° the disturbed state was formed only in part of the sample. The disturbed state was also formed if a large enough resonant continuous RF excitation (∼0.01 Oe) was applied to the sample while cooling down through T_{ca}. In the longitudinal field the disturbed state did not form after any tipping pulses or continuous excitation were applied in the vicinity of T_{ca}. Also the NMR lines in either state did not change after application of any RF excitation below $\approx 0.95T_{ca}$. The disturbed state proved to be stable: no change in the NMR line was seen over a period of one day.

The spin dynamics of the disturbed state turned out to be very different from the dynamics of the undisturbed state. The most evident difference

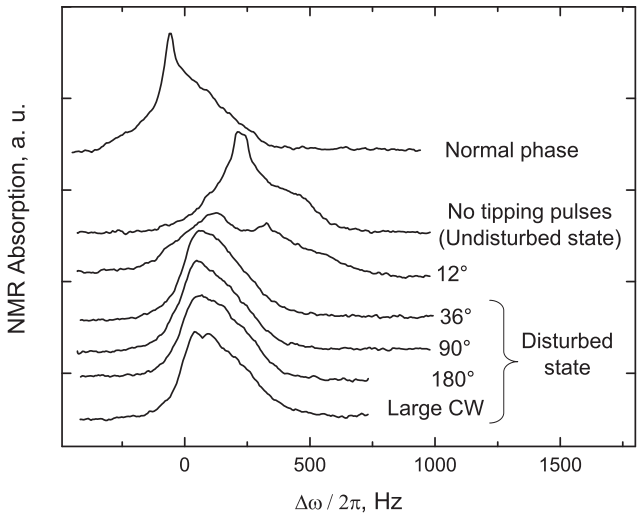

Figure 1: CW NMR lines in the undisturbed and disturbed states in transverse field in sample 1. The top line was observed above T_{ca}, all other lines at $T=0.89\,T_{ca}$. The conditions in the vicinity of T_{ca} are indicated next to the lines, numbers are amplitudes of the corresponding tipping pulses (see text). The external field was perpendicular to the sample axis. For clarity the zero levels of absorption are shifted. H=118 Oe, P=26.0 bar, $T_{ca}=0.80\,T_c$.

was in the magnitude of the NMR frequency shift from the Larmor value. In sample 2 the shift in the disturbed state was 2 times smaller than in the undisturbed state (Fig. 2). We think that in sample 1 the anisotropy was not spatially homogeneous because the width of the NMR line in the A-like phase was large. Netherveless we were able to cool the sample down to the A-like→B transition and then warm up so that the A-like phase survived only in part of the sample and the other part was in the B-phase. In this case only the most shifted part of the A-like phase signal (corresponding to the region where $\mathbf{l}\|\hat{\mathbf{z}}$) remained[2]. The opposite phenomenon of survival of the less shifted part was observed in[1]. The A-like phase NMR lines in both states obtained after such a procedure were rather narrow and the ratio of the shifts in the disturbed and undisturbed states was close to 3.

We were also able to slowly rotate $\mathbf{H}$ when our sample was in the disturbed state. The frequency shift of the NMR line became negative in the longitudinal field but smaller (in absolute value) than in the undisturbed

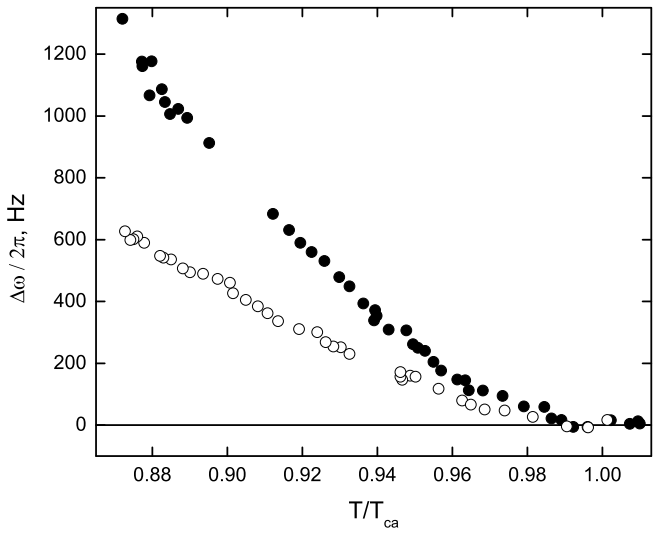

Figure 2: Shifts of the mean resonant frequency in the disturbed (○) and undisturbed (●) states in transverse field in sample 2. The shift in the disturbed state was about 2 times smaller than in the undisturbed state. H=97.5 Oe, P=28.6 bar. T_{ca}=0.82 T_c.

state. No changes in the NMR line were observed when the field was returned to the transverse orientation. What is more surprising is that the disturbed state was not modified when we decreased the magnetic field down to no more than 0.5 Oe and returned the field to its former value.

In sample 1 we have also carried out longitudinal NMR experiments. In these experiments we swept the temperature while recording the signal from the longitudinal NMR coil. Because the axis of this coil was oriented along $\hat{\mathbf{z}}$ we were not able to see any signal for transverse orientation of $\mathbf{H}$. Therefore we used angles $\psi = 0°$ and $60°$ between $\mathbf{H}$ and $\hat{\mathbf{z}}$. As is expected for the ABM order parameter no longitudinal NMR was found in the undisturbed state for $\psi = 0°$. For $\psi = 60°$ the longitudinal NMR signal in the undisturbed state was clearly seen and its position on the temperature axis was in a good agreement with that expected from the value of the frequency shift measured by transverse NMR[2]. On the other hand for $\psi = 60°$ no response in the disturbed state was observed in the experiments on longitudinal resonance down to transition to the B-phase.

One more difference between the two states is demonstrated by the results

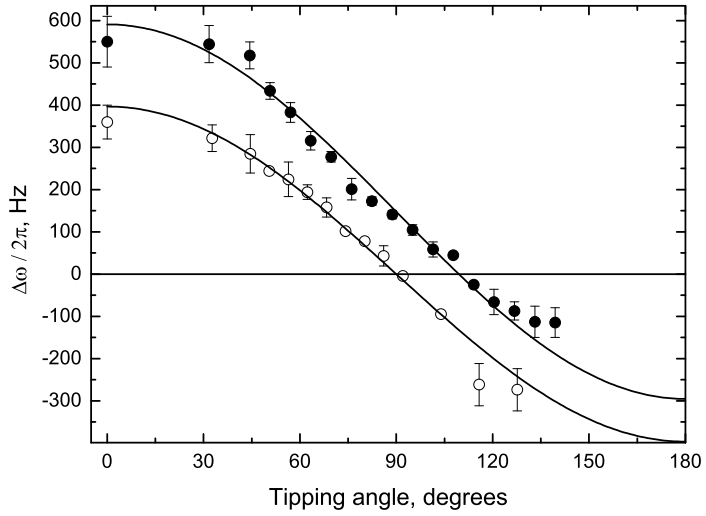

Figure 3: Frequency shift as a function of the magnetization tipping angle β in pulsed NMR experiments in sample 2 in transverse field. In the disturbed state (○) the shift fitted to $A_1 \cdot \cos\beta$ with $A_1 = 395$ Hz and in the undisturbed state (●) the shift fitted to $A_2 \cdot (1 + 3\cos\beta)/4$ with A_2=590 Hz. The points at zero tipping angle are from CW NMR measurements. H=97.3 Oe, P=28.6 bar. The temperature was $0.928\mathrm{T}_{ca}$ for the disturbed state and $0.933\mathrm{T}_{ca}$ for the undisturbed state.

of the pulsed NMR shown in Fig.3. We have found that in the disturbed state the frequency shift depends on the tipping angle β as $\Delta\omega_{dist}/2\pi = A_1 \cdot \cos\beta$, while in the undisturbed state the dependence was like in the ABM phase: $\Delta\omega_{undist}/2\pi = A_2 \cdot (1 + 3\cos\beta)/4$.

4 Conclusions

The properties of the disturbed state are very different from the properties of the undisturbed state. First, the NMR shift is several times smaller in the disturbed state. Second, no longitudinal resonance was observed in this state. Third, the NMR frequency shift depends on the tipping angle as $\Delta\omega_{dist}/2\pi = A_1 \cos\beta$.

The origin of the disturbed state is unclear. While the properties of the

undisturbed state can clearly be related to the A phase order parameter with the vector $\mathbf{l}$ fixed by anisotropy, the properties of the disturbed state can not be explained in terms of this order parameter in a straightforward manner. It is probable that the disturbed state corresponds to textural domain walls ("solitons") similar to those existing in the A phase of bulk ^{3}He[6, 7, 8, 9]. It is known that textural defects (at least vortices in the B-like phase) can be strongly pinned by aerogel[10]. In our case solitons can appear near T_{ca} due to motion of the spin part of the order parameter and at lower temperature can be pinned by aerogel, which may explain their stability. However, not all properties of the disturbed state can be explained by the soliton model. It is not clear how tipping pulses as small as 12° can create domain walls of the order parameter vectors: it is known that in the bulk A phase solitons can be created only with much larger pulses[6, 7]. We should also note that in the disturbed state the whole NMR line is changed while solitons in the A phase either manifest themselves as small satellite peaks to the main NMR line (i.e. solitons occupy only small part of the sample) or are unstable (disappearing after a time of the order of a minute). Also the difference in NMR shifts between the bulk ^{3}He-A with solitons and defectless superfluid is not as large as in the case of the disturbed and undisturbed states in aerogel. Note that tipping pulses altered the undisturbed state only in the vicinity of T_{ca} where the behavior of the A-like phase in anisotropic aerogel is not described by the model of spatially homogeneous A phase: as was found in[2] the NMR shift in the A-like phase at these temperatures is close to zero and starts to grow only below $\sim 0.98\, T_{ca}$. No RF excitation can further influence the disturbed or undisturbed states at lower temperatures, while in the bulk A phase solitons can be created in a broad range of temperatures, down to $0.9T_c$.

Properties of the so-called *c*-state observed earlier in (presumably) isotropic the A-like phase[11] are qualitatively the same as the properties of the disturbed state. The *c*-state was also formed by RF pulses applied near T_{ca} and its NMR line had also frequency shift a few times smaller than the standard NMR line. However we can not confidently identify the disturbed state with the *c*-state because the value of the NMR shift in the *c*-state was typically about 5 times smaller than in the disturbed state (in samples 1 and 2) at similar conditions, and in a longitudinal field the shift was positive. We should note that in the sample used in[11] the shift of a standard A-like phase NMR line in longitudinal field was also positive and its value was much smaller than in the undisturbed state in the anisotropic aerogel. Presumably it was

due to the squeezing of the sample in transverse plane by spacers on the side walls of the cell. This could decrease the intrinsic anisotropy of the sample, so the A-like phase order parameter could be different from the homogeneous A phase order parameter[2]. It also makes a direct comparison of the disturbed state and the c-state impossible.

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